CLUSTER II: FROM LAUNCH TO FIRST CONSTELLATION

Roberta MUGELLESI DOW
John DOW
Gottlob GIENGER

European Space Agency/European Space Operations Center
Robert-Bosch-Strasse 5, 64293, Darmstadt, Germany
Roberta.Mugellesi.Dow@esa.int, John.Dow@esa.int, Gottlob.Gienger@esa.int,

ABSTRACT *– The paper highlights the challenging aspects of the Cluster II mission from both the operations and flight dynamics points of view: the double dual launch using two Russian Soyuz rockets, upgraded with a new Fregat upper stage and each carrying a pair of spacecraft; the operations during the Launch and Early Orbit Phase executed under high time pressure; the sequence of orbit manoeuvres involving all four spacecraft with the aim of achieving a satellite constellation forming a regular tetrahedron; the deployment of 5 m rigid booms and four 43 m flexible cable booms on each satellite involving several attitude slews, and spin rate adjustments spread over more than three months of the payload commissioning phase. Proximity control of the spacecraft is discussed, presenting the strategy used to keep the inter-spacecraft distance within the limits. The paper outlines the operational constraints and problems that had to be resolved in the definition of the mission timeline, and the major mission operations and flight dynamics activities that were performed during the first six months of the mission.*

INTRODUCTION

The Cluster II spacecraft were launched in July and August 2000 and now slightly more than one year of successful operations and commissioning activities, the Cluster quartet has been flying in formation through two regions of scientific interest. These are the polar cusp region of the magnetosphere, in March 2001, and the geomagnetic tail in September 2001. The spacecraft were built by an industrial consortium led by Astrium GmbH. The challenging aspects of this unique mission from both the operations and flight dynamics points of view were both the double dual launch using two Russian Soyuz rockets and the simultaneous control of two and then of four identical spacecraft, to achieve a precisely defined constellation. The operations were carried out by the European Space Operations Centre (ESA/ESOC) in Darmstadt, Germany, and required full support of the Operations and Flight Dynamics teams around the clock for the first week after each launch. The ground station network comprises also non-ESA stations. This required the setting up of dedicated interfaces with the NASA Deep Space Network for the use of Canberra. This paper describes the operations and the flight dynamics activities during the early orbit phase of the mission (initial 12 hours after each launch), during the transfer phase of each spacecraft into an orbit close to the operational orbit and subsequent correct positioning, and lists the activities necessary for the deployment of the rigid and the wire booms, that marked the beginning of the commissioning phase. The four spacecraft will spend the remaining operational life, at least two years in total, passing in and out of the Earth's magnetic field through regions of key scientific interest with respect to the Earth's interaction with the solar wind, in particular cusp crossings and geomagnetic tail crossings. A challenging aspect of this mission was also the selection of the target orbits for each spacecraft to ensure that the scientific requirements were met with the available fuel on-board. By flying in a tetrahedron formation, the spacecraft are able to make three-dimensional studies of the small scale features, when a few hundred kilometres apart, or of large scale features, when at larger distances. Fig. 1 shows in bold the mean target orbit, called mission orbit, passing inside and outside the geomagnetic field. The orbital plane rotates approximately once per year around the Earth-Sun line.

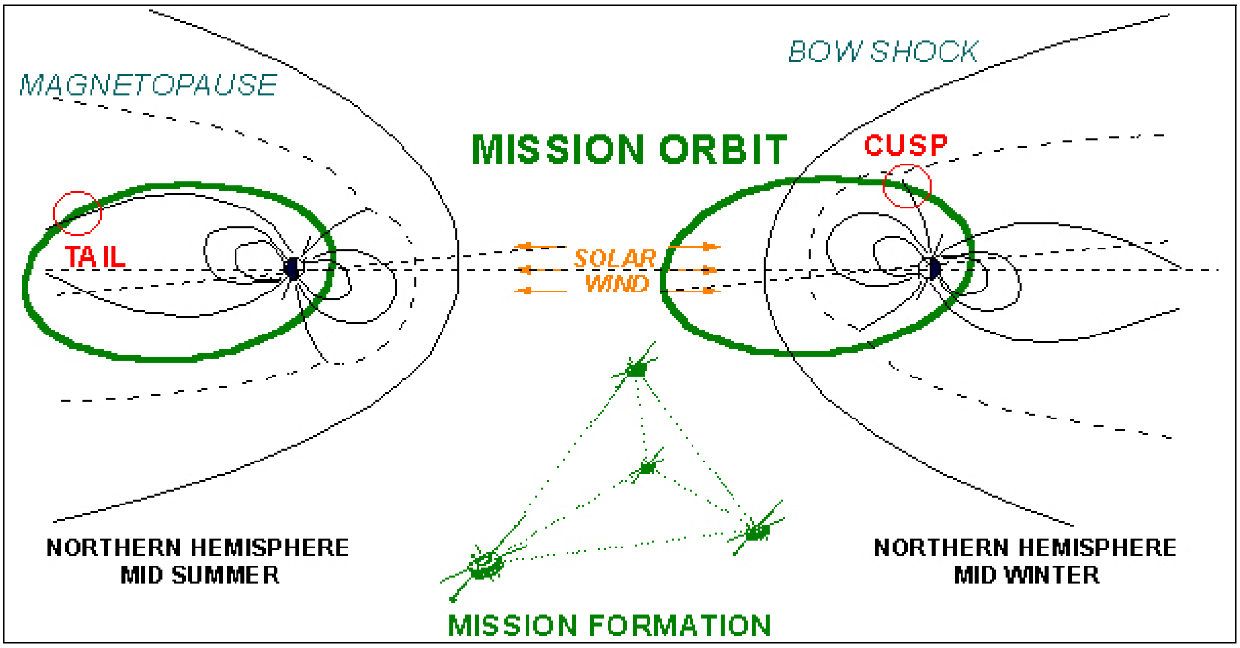

Fig. 1. The mission orbit

THE LAUNCH

An innovative aspect of this mission was the double dual launch using two Russian Soyuz rockets, upgraded with a new Fregat upper stage, and each carrying a pair of spacecraft. This choice led to some important consequences: a new launch scenario with highly elliptical and inclined separation orbit; operational support of two launches in four weeks; and setting up new interfaces with the French/Russian launch authority Starsem and the Russian Lavochkin industrial complex. From the sub-orbital trajectory achieved by Soyuz, the Fregat upper stage motor brought the spacecraft pair first into a circular parking orbit at about 220 km altitude and then into an elliptic transfer orbit, where the separation of each spacecraft took place. The Soyuz/Fregat trajectory is depicted in Fig.2.

The first Soyuz launch, carrying the first pair of Cluster spacecraft, occurred on 16 July 2000 at 12:39:34 UTC from Baikonour Cosmodrome in Kazakhstan. During the Soyuz/Fregat flight a continuous voice link was established between the ESOC Flight Dynamics team and ESOC Mission Analysis/Lavochkin personnel in Moscow reporting the occurrence of all the expected events on schedule. The Soyuz launcher placed the composite of Fregat upper stage and the two spacecraft in an orbit inclined at 64.8° to the equator. Once the booster reached the correct altitude, 8 minutes 48 seconds after lift-off, the composite was released. The Fregat main engine fired almost immediately to achieve the circular parking orbit of 220 km altitude. The orbital elements of the parking orbit were reported by Lavochkin to be nominal. After a coast phase of about 1 hour, the second Fregat burn occurred to inject the two spacecraft into the separation orbit. The burn occurred out of the ground station contact, and information on the successful separation and therefore acquisition by the Russian ground stations was at the predicted times. The separation of the two Cluster spacecraft occurred at 1h 30 min. after lift-off in an initial orbit having a semimajor axis of 15534 km and an orbital inclination of 64.88 deg. The first spacecraft to be separated was s/c 3, followed by s/c 2. The differences in the initial velocities of both spacecraft were dictated by the separation spring forces acting. At the time of separation, the spacecraft were spin stabilised at the nominal 5 rpm. The first ESA ground station to have visibility was Kiruna (Sweden). It acquired the lower s/c 2 at 14:11:53 and the s/c 3 about 9 minutes later due to the occurrence of a computer memory unit switchover on board of the latter spacecraft.

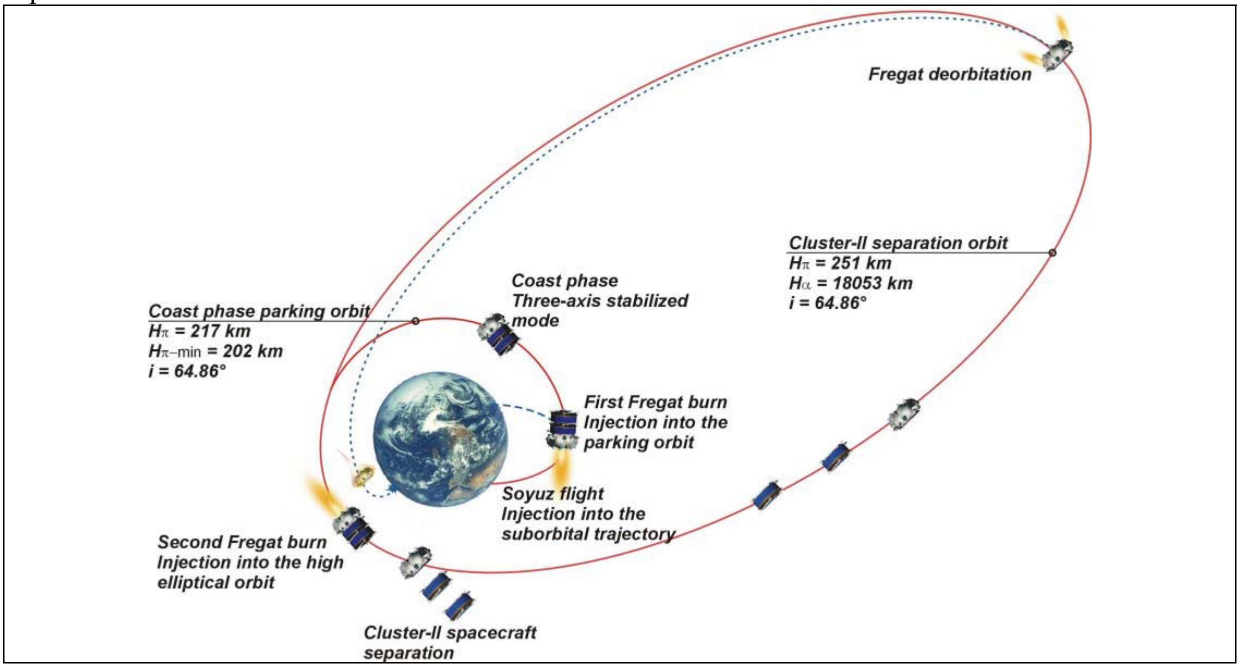

Fig. 2. Trajectory of Soyuz-Fregat

For orbit determination purposes it was decided that one spacecraft should receive the full tracking data from the Kiruna station. The rationale for this was to be able to complete within the visibility as much as possible operations over one spacecraft, whilst to allow as soon as possible a preliminary orbit determination for at least one spacecraft. The orbit determination results were used as a first approximation for the orbit of the other spacecraft, by taking into account the known velocity differences of the spacecraft caused by the springs during separation. The subsequent passes of Canberra and Perth were used to accurately estimate the orbits at four hours after separation. The first ESOC orbit determination was available at 14:53 UTC, and showed very good agreement with the predictions and with the results provided later by the launch authority. It was decided to perform tracking only for s/c 3, and so for s/c 2 the orbit was approximated from the results of s/c 3 by adding the spring forces. The final determined orbital elements and their accuracy for s/c 3 are given in the Table 1. The results for s/c 2 were similar.

Table 1. Orbital elements at separation time and respective accuracy for s/c 3

	Determined Elements	Final OD - Nominal	Final OD – First OD
Date	16/07/2000		
Time	14:10:10		
A (km)	15533.945	11.06	-0.62
E	0.573689	0.0003	0.0001
I (deg)	64.879	0.02	0.02
RA (deg)	160.210	0.03	0.06
A.Pe.(deg)	0.979	-0.02	-0.02
T. A.(deg)	44.351	0.01	0.01

The initial attitude of both spacecraft was nominal and the nutation damped quickly from 0.5 deg to 0.1 deg as expected. The launch of the second pair of spacecraft occurred as planned four weeks after the first launch. The separation orbit to be achieved was the same as for the first launch, whereas phasing with the first pair was achieved by a proper selection of the sequence of manoeuvres to reach the operational orbit. The launch of the second pair occurred on the 9 August 2000 at 11:13:35 UTC. As with the previous launch, a voice link with Lavochkin was established to provide confirmation of the flight events. Around 20 minutes after launch it was reported that an underperformance of the Soyuz launcher of about 100 m/sec occurred and this was compensated by the Fregat first burn. As a consequence, it was anticipated that the Fregat second burn could be about 30-70 m/sec less than nominal, implying an apogee height of the separation orbit about 700 km lower than nominal.

On the basis of the data provided from Lavochkin, Flight Dynamics estimated the resulting off-pointing for the ground stations involved in the initial acquisition: 0.4 deg for Kiruna and 1 deg for Canberra. Subsequently new station predictions for both stations taking into account the latest orbit prediction results were generated. This timely information from Lavochkin allowed the initial acquisition from Kiruna for both spacecraft to occur without any complication, despite the initial Soyuz under-performance. The preliminary orbit determination results based only on the first pass of Kiruna confirmed an apogee height about 1000 km lower than the nominal value and this was in agreement with the value provided later by Lavochkin for Fregat. The final determined orbital elements for s/c 1 are given in the Table 2 and are compared with the first orbit determination results computed about two hours after the launch and based only on the Kiruna tracking data. Similar were the determined orbital elements for s/c 4. As for the first launch, one spacecraft (s/c 1) received all the tracking from Kiruna, therefore its orbit was determined, whereas for the other spacecraft (s/c 4) the orbit was only approximated. The initial attitude of both spacecraft was confirmed by the received telemetry to be nominal and the nutation again damped quickly from 0.5 deg to 0.1 deg.

Table 2. Orbital elements at separation time and respective accuracy for s/c 1

	Determined Elements	Final OD - Nominal	Final OD – First OD
Date	09/08/2000		
Time	12:43:26		
A (km)	15046.493	-481.53	-2.75
E	0.559930	-0.0136	-0.0001
I (deg)	64.831	-0.03	0.01
RA(deg)	162.236	-0.05	0.02
A.Pe.(deg)	357.724	-0.27	0.02
T. A.(deg)	44.218	-0.10	-0.01

THE LAUNCH AND EARLY ORBIT PHASE

The Launch and Early Orbit Phase was one the most demanding phases of the mission, where intense operations were executed under high time pressure. Major activities such as the initial acquisition of both spacecraft from the ESA ground stations, the first switch-on of the different subsystems, the priming of all valves and thrusters, the spinning up of each spacecraft to the operational rate had to be completed for both spacecraft within the first four hours from launch to allow the start of the first attitude manoeuvre at the planned time.

The major activities performed by the Flight Control team were: the initial status check, the On-board Data Handling System initialisation, the Reaction Control System (RCS) priming, execution of the spin-up manoeuvre and of the attitude manoeuvre required for the first apogee raising manoeuvre. The activities performed by the Flight Dynamics team were: initialisation and check-out of the system, preparation and monitoring of the spin-up manoeuvre, orbit and attitude determination, preparation and monitoring of the attitude slews, preparation of the commands for the first orbit manoeuvre. Due to the heavy commanding, especially during the first hour after separation, and due to the fact that it was not always possible to perform ranging and commanding together, the acquisition of the ranging followed a predefined scheme to ensure that the required tracking data were provided to Flight Dynamics. The ground station network used comprised the Kourou, Villafranca, Perth and Canberra stations, complemented by a few passes of Kiruna. The first contact occurred at Kiruna, at about 7 minutes after separation for the following 40 minutes. This was followed by Canberra after about 30 minutes, followed by Perth some 10 minutes later, and then Villafranca and Kourou. The maximum pass duration was 215 minutes. Only one spacecraft received the full tracking data from Kiruna. The subsequent passes were almost equally allocated to both spacecraft.

In parallel to the orbit determination activities, the telemetry data were collected and processed to provide, on the basis of the sun sensor data, information on the solar aspect angle and on the spin rate of the spacecraft. Special contingency procedures were developed and extensively tested during the pre-launch simulations campaign giving instructions to be followed in case of non-nominal spin rate values or non nominal solar aspect angle in order to return to the nominal status. The attitude was determined by using measurements from the star mapper, after it was switched on, early on the Kiruna pass. After the spin-up, the spin rate and the spacecraft attitude were obtained from the high precision sun sensors and the star mapper data. Special attention was devoted to the star mapper data quality due to the higher rate of spurious events, especially at high temperatures (to be mentioned here is the historic geomagnetic storm on 15.07.2000). The requirement to cope with the larger noise of the star mapper was critical for the attitude determination subsystem.

Once the initial checkout, switching on of the Attitude and Orbit Control and Monitoring System (AOCMS) and the RCS priming were completed, the two spacecraft were ready to execute the spin-up manoeuvre increasing the spin rate from 5 to 14 rpm. These manoeuvres occurred as planned at about 4 hours after launch around the first apogee. The rationale for this was to have the spacecraft properly set to be able to perform emergency perigee raising manoeuvre around the first apogee (and with current attitude) in case of the contingency of low injection perigee. All spin-up manoeuvres were executed using the 2x10 N radial thrusters in continuous mode. Typical duration of the manoeuvre was 92 seconds and generating a delta-v of about 0.7 m/sec on the orbit. The accuracy of the spin-up manoeuvres were of 0.1 %, apart from s/c 1 where an under-performance of 2.3% was seen. An accurate thruster model for both the 10 N thrusters and for the main engine and also for the tanks was developed and used by Flight Dynamics to accurately compute the fuel used during each activation, to predict the remaining fuel on-board and to predict the changes in the inertias. The spacecraft at this point were configured to start the sequence of attitude and orbit manoeuvre for the transfer to the operational orbits.

TRANSFER ORBIT PHASE

Each spacecraft was separately manoeuvred to achieve the orbit targets for the first cusp crossing about six months later. The target orbits had 19.6 R_e as apogee radius, 4 R_e as perigee radius and an orbital inclination of 90 deg. Fig. 3 shows the evolution of the shape and the orientation of the tetrahedron in the target orbit. A regular tetrahedron is required at the north and south cusp crossings.

The target apogee radius was achieved through a sequence of tangential burns performed at perigee, each lasting about 10 minutes. Each spacecraft was planned to be manoeuvred after four revolutions into the separation orbit through various intermediate orbits, according to a sequence of events, which was extensively tested during the pre-launch simulations and system test campaign. A series of four apogee raising manoeuvres and a large inclination change manoeuvre were to be executed for each spacecraft. The four Apogee Raising manoeuvres were needed to raise the apogee height from the initial value of 3.8 Re to 19.6 Re. This corresponded to a total delta-v of about 966.4 m/sec. As result of the burns, the resulting orbits had longer periods, from the initial period of 5.3 h, to 7.1 h, 10.3 h, 18 h and 47.3 h. The firings were in-plane manoeuvres performed around subsequent orbital perigees.

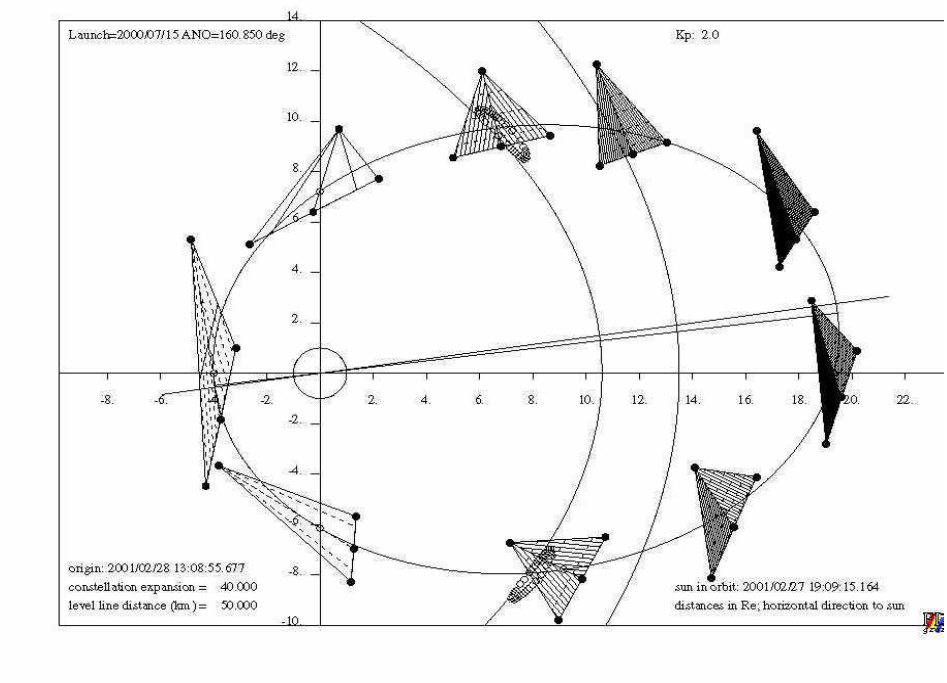

Fig. 3. Constellation evolution in the target orbit

Fig. 4 is a projection on the orbital plane of the intermediate orbits for the first launch. The first pair of spacecraft was manoeuvred together. The preparations for attitude and orbit manoeuvres and the execution of the attitude manoeuvres (requiring real-time monitoring) were performed in sequence, whereas the orbit manoeuvres (without ground stations visibility) were executed almost at the same time for the two spacecraft. In case of delay of one orbit manoeuvre due to problems encountered during the preparation or in the event of failure of an orbit manoeuvre occurring during the execution, a suitable backup strategy or a complete new planning process could be needed. Both cases were addressed in the contingency procedures, which had been exercised before launch. The time between subsequent manoeuvres was about 20 hours, roughly the time needed to complete 3 revolutions in the first intermediate orbit, 2 revolutions in the second intermediate orbit and only one revolution in the third intermediate orbit. All manoeuvres were performed according to the prepared sequence of events.

Attitude manoeuvres were required to align the spin axis to the attitude required for the burn. Such manoeuvres were performed using the 10N thrusters in pulsed mode to turn the spin axis. The first attitude change manoeuvres were required to align the spin axis to the velocity vector at perigee, optimal direction for the apogee raising manoeuvre. In order to decrease the number of attitude changes for the apogee raising manoeuvres it was decided to target since the beginning to an attitude equivalent to the arithmetic mean of the four optimal attitudes. Table 3 lists the manoeuvres executed during the transfer phase by each spacecraft. A total of 105 manoeuvres were performed between launch of the first Cluster II pair and the achievement of the first exact constellation, including the many attitude related manoeuvres involved in boom deployments, with delta-v ranging from 450 m/s for the inclination manoeuvres to <1 mm/s for constellation orbit trims.

Throughout the transfer phase, the relative distances between the spacecraft were monitored. Therefore, as part of the preparation of each burn, the relative distances during all subsequent manoeuvres were computed. A parametric analysis was carried out to determine the minimum of the inter-spacecraft distances resulting from a range of errors in the spin axis pointing and delta-v magnitude. Then the delta-v required for the next burn was increased or decreased for each spacecraft with respect to the nominal optimal value by a small percentage so as to ensure that the relative distance would remain above a given safe value. The relative distances were checked again with the modified delta-v to confirm the safe distance. The iteration was repeated if necessary.

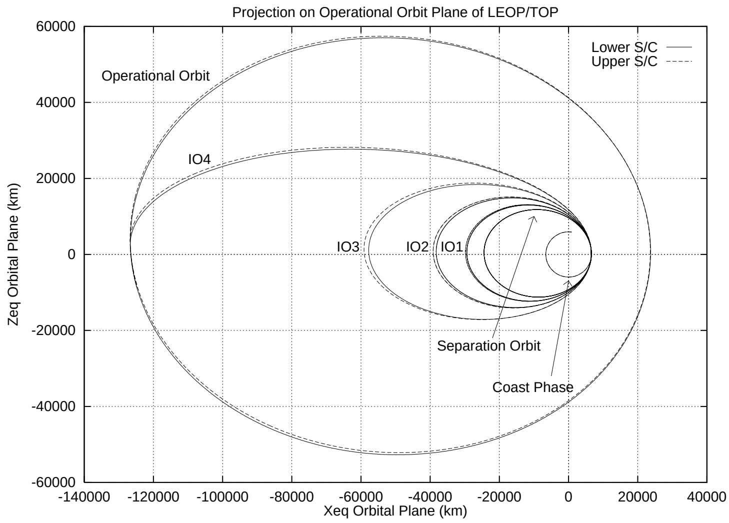

Fig. 4. Intermediate orbits during first launch

Fig. 5 is an example of the performance plot for the first apogee raising manoeuvre. Each level line corresponds to all solutions for which a given minimum distance could be expected. Special attention was paid to the first orbit manoeuvre. At separation s/c 3 was slightly ahead of s/c 2, but s/c 2 following the optimisation results started the manoeuvre one minute before s/c 3. Both spacecraft had a main engine under-performance, specifically 1% for s/c 3 and 1.3% for s/c 2. As result of these circumstances, there had been a minimum distance of 4.2 km between the two spacecraft at the following apogee. For the next manoeuvre it was decided to increase by 1% the delta-v for s/c 3 and to decrease by 1% the delta-v for s/c 2 to ensure a safe separation distance between the two spacecraft. This strategy was proven to be successful for all successive manoeuvres, where the minimum distance was kept always above 150 km. Calibration of the subsequent main engine manoeuvres demonstrated very high consistency with respect to these calibration values (less than 0.2 %). On the basis of the experience of the first pair of spacecraft, it was then decided that for the second pair the same strategy of ensuring safe distance should be followed. In addition, due to the uncertainty of the main engine performance, it was decided just for the first orbit manoeuvre not to execute the orbit manoeuvre for both spacecraft at the same orbital perigee, but to keep them separated by one orbital revolution. Therefore, s/c 4 performed the first orbit manoeuvre at the fourth perigee, and s/c 1 at the fifth perigee

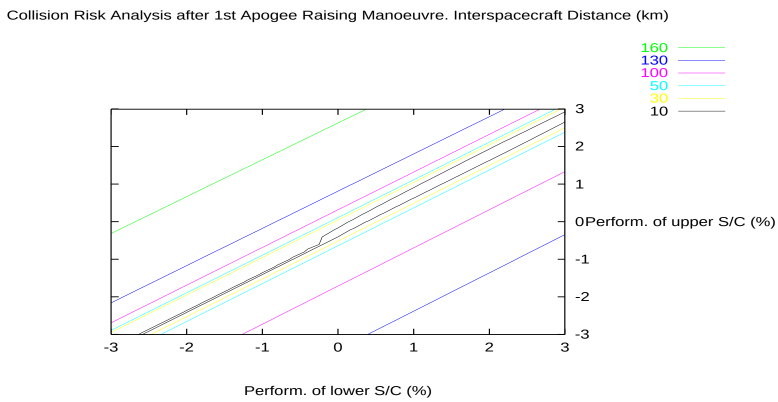

Fig. 5. Deltav performance plot (% ΔV error) for first apogee raising

This difference in time was then compensated during the successive manoeuvre, such that at the time of the third apogee raising the two spacecraft were again executing the manoeuvre almost at the same time. To achieve the target orbits, it was necessary, once the apogee raising sequence was completed, to perform an inclination correction/perigee raising manoeuvre to increase the orbital inclination from 64.7 to 90 deg and to raise the perigee height to almost the target value. This manoeuvre was performed close to the apogee. The optimal thrust direction required a big attitude change manoeuvre with a turn angle of about 90 deg. Fig. 6 shows the inter-spacecraft distance during the transfer phase of the second pair of spacecraft. In addition, the error analysis, showed that the success of this orbit manoeuvre was very dependent on the accuracy of the thrusting direction and timing of the manoeuvre. Therefore, to achieve the requested accuracy, an attitude trim was necessary after the main attitude change to achieve the accuracy required of 0.1 deg in the burn direction.

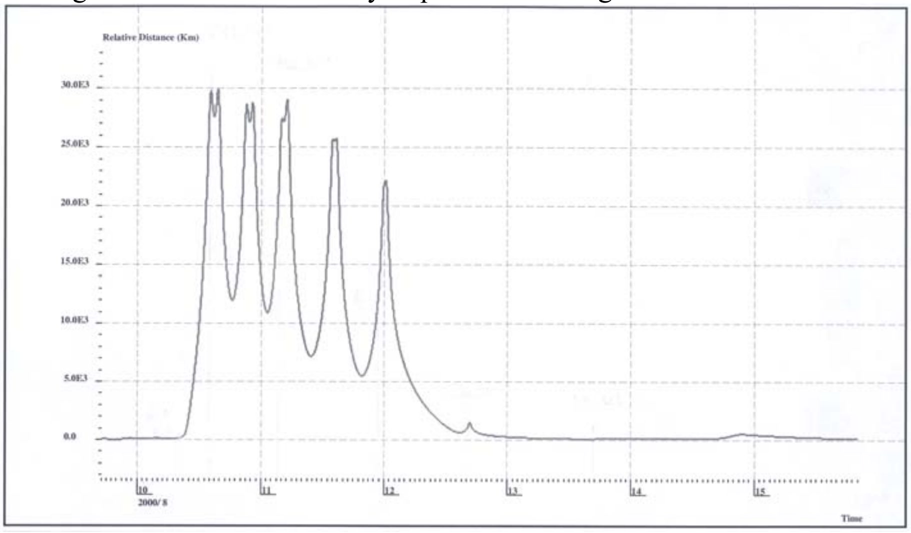

Fig. 6. Relative distance of the second pair during the transfer phase

The period between the two Soyuz launches lasted four weeks. During the remainder of this period, the major activities of flight dynamics were: monitoring the orbit and attitude of the first pair of spacecraft, fine tuning of the target orbits of the second pair of spacecraft taking into account the experienced launcher dispersion, manoeuvre dispersions and the operational orbits achieved by the first pair of spacecraft, and of course finalisation of the sequence of events for the second launch. As for the first launch, a reference baseline sequence of events for the second pair, in terms of number of intermediate revolutions/manoeuvres and ground station availability, was created and extensively tested. With launch postponement of more than one day, changes in the sequence of events would have occurred to enable the rendezvous with the spacecraft of the first pair. The backup sequence of events was pre-prepared and tested. The execution of the inclination manoeuvre of the second pair of spacecraft was the last main engine manoeuvre and marked the end of the highly demanding transfer orbit phase, six days after the second launch. Fig. 7 is a picture showing the relative position of the four spacecraft at the time of the execution of the inclination manoeuvres of the second pair.

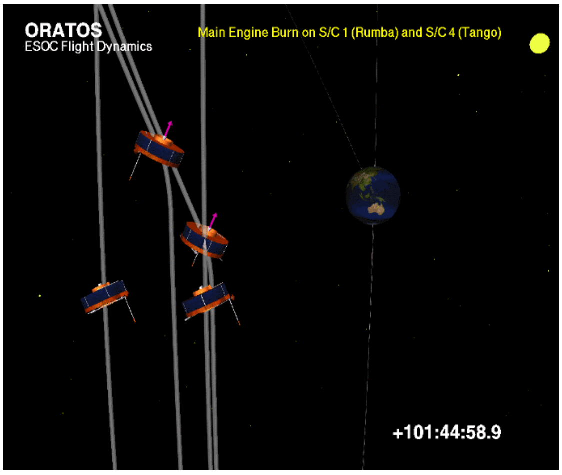

Figure 7 – Inclination manoeuvre of the second pair

Table 3 - Cluster II LEOP/TOP manoeuvres

S/C	Date	Time	Type	Duration	Description
3	2000-07-16	18:12	10 N thrusters	94 s	Initial spin-up from 5 to 14 rpm
3	2000-07-16	23:00	10 N thrusters	51 s	Slew to apogee raising attitude
3	2000-07-17	11:22	Main engine	10.5 min	Apogee raising manoeuvre 1
3	2000-07-18	08:33	Main engine	10.26min	Apogee raising manoeuvre 2
3	2000-07-19	05:18	Main engine	10.01min	Apogee raising manoeuvre 3
3	2000-07-19	23:24	Main engine	9.5 min	Apogee raising manoeuvre 4
3	2000-07-20	03:40	10 N thrusters	21.6 min	Slew to inclination change attitude
3	2000-07-20	11:00	10 N thrusters	16 s	Attitude trim
3	2000-07-21	00:04	Main engine	17.9 min	Inclination change manoeuvre
3	2000-07-21	04:30	10 N thrusters	41 s	Spin-down to operational rate
3	2000-07-21	15:00	10 N thrusters	6.7 min	Slew to operational attitude
2	2000-07-16	18:32	10 N thrusters	96 s	Initial spin-up from 5 to 14 rpm
2	2000-07-16	21:45	10 N thrusters	39 s	Slew to apogee raising attitude
2	2000-07-17	11:21	Main engine	10.6 min	Apogee raising manoeuvre 1
2	2000-07-18	08:28	Main engine	10.6 min	Apogee raising manoeuvre 2
2	2000-07-19	05:00	Main engine	10.4 min	Apogee raising manoeuvre 3
2	2000-07-19	22:59	Main engine	9.8 min	Apogee raising manoeuvre 4
2	2000-07-20	06:57	10 N thrusters	22.0 min	Slew to inclination change attitude
2	2000-07-20	14:10	10 N thrusters	22 s	Attitude trim
2	2000-07-20	23:02	Main engine	18.3 min	Inclination change manoeuvre
2	2000-07-21	06:00	10 N thrusters	41 s	Spin-down to operational rate
2	2000-07-21	17:00	10 N thrusters	6.7 min	Slew to operational attitude
1	2000-08-09	15:42	10 N thrusters	92 s	Initial spin-up from 5 to 14 rpm
1	2000-08-09	21:40	10 N thrusters	25 s	Slew to apogee raising attitude
1	2000-08-10	13:59	Main engine	11.5 min	Apogee raising manoeuvre 1
1	2000-08-11	03:40	Main engine	10.4 min	Apogee raising manoeuvre 2
1	2000-08-11	23:35	Main engine	10.0 min	Apogee raising manoeuvre 3
1	2000-08-12	16:35	Main engine	10.3 min	Apogee raising manoeuvre 4
1	2000-08-12	23:35	10 N thrusters	21.5 min	Slew to inclination change attitude
1	2000-08-13	06:40	10 N thrusters	13 s	Attitude trim
1	2000-08-13	16:58	Main engine	17.2 min	Inclination change manoeuvre
1	2000-08-14	11:15	10N thrusters	39 s	Spin-down to operational rate
1	2000-08-14	14:45	10 N thrusters	6.3 min	Slew to operational attitude
S/C	Date	Time	Type	Duration	Description
4	2000-08-09	16:14	10 N thrusters	96 s	Initial spin-up from 5 to 14 rpm
4	2000-08-09	18:13	10 N thrusters	30 s	Slew to apogee raising attitude
4	2000-08-10	08:53	Main engine	10.9 min	Apogee raising manoeuvre 1
4	2000-08-11	04:58	Main engine	10.7 min	Apogee raising manoeuvre 2
4	2000-08-12	00:18	Main engine	10.2 min	Apogee raising manoeuvre 3
4	2000-08-12	16:38	Main engine	11.1 min	Apogee raising manoeuvre 4
4	2000-08-12	20:40	10 N thrusters	21.8 min	Slew to inclination change attitude
4	2000-08-13	03:30	10 N thrusters	26 s	Attitude trim
4	2000-08-13	16:55	Main engine	17.5 min	Inclination change manoeuvre
4	2000-08-14	10:15	10 N thrusters	45 s	Spin-down to operational rate
4	2000-08-14	13:15	10 N thrusters	6.2 min	Slew to operational attitude

Table 4 - Orbit and attitude trims after LEOP/TOP 2 up to the end of rigid boom deployments

Date	Time	Spacecraft	Dur. (sec)	Thrusters	Description
2000-08-15	22:00	2	23	3A+4A	Apogee radial trim
2000-08-16	21:09	3	20	3A+4A	Apogee radial trim
2000-08-17	05:35	1	53	2A	Drift start
2000-08-17	05:39	4	16	2A	Drift start
2000-08-17	16:30	1	659	1A+2A	Slew to SAA 81, rigid boom start
2000-08-17	19:50	1	87	3A+3B+1A+1B	Spin-down to 4.5 rpm
2000-08-17	22:00	1	101	4A+4B+1A+1B	Spin-up to 15 rpm
2000-08-17	22:40	1	140	1A+2A	Slew back, rigid boom end
2000-08-18	06:56	4	32	3A+4A	Apogee radial trim
2000-08-18	12:00	4	685	1A+2A	Slew to SAA 81, rigid boom start
2000-08-18	14:30	4	84	3A+3B+1A+1B	Spin-down to 4.5 rpm
2000-08-18	17:10	4	101	4A+4B+1A+1B	Spin-up to 15 rpm
2000-08-18	18:45	4	136	1A+2A	Slew back, rigid boom end
2000-08-19	14:30	3	13	1A+1B	Perigee axial trim
2000-08-19	14:40	2	702	1A+2A	Slew to SAA 81, rigid boom start
2000-08-19	18:00	2	84	3A+3B+1A+1B	Spin-down to 4.5 rpm
2000-08-19	19:45	2	101	4A+4B+1A+1B	Spin-up to 15 rpm
2000-08-19	21:00	2	140	1A+2A	Slew back, rigid boom end
2000-08-20	11:45	3	688	1A+2A	Slew to SAA 81, rigid boom start
2000-08-20	15:05	3	88	3A+3B+1A+1B	Spin-down to 4.5 rpm
2000-08-20	16:50	3	101	4A+4B+1A+1B	Spin-up to 15 rpm
2000-08-20	18:15	3	138	1A+2A	Slew back, rigid boom end
2000-08-20	19:24	2	40	1A+1B	Apogee axial trim
2000-08-23	02:07	1	32	2A+2B	Apogee axial trim
2000-08-23	03:59	4	41	2A+2B	Apogee axial trim
2000-08-24	08:44	2	12	2A+2B	Drift stop
2000-08-24	09:17	3	45	2A+2B	Drift stop
2000-08-26	17:36	1	16	1A+1B	Drift stop
2000-08-26	18:04	3	4	2A+2B	Perigee axial trim
2000-08-26	18:06	4	4	1A+1B	Perigee axial trim

Table 5 - Typical sequence of manoeuvres for the wire boom deployment

Date	Time	S/C	Duration	Description
2000-10-25	17:56	4	4.8 min	Wires 3 and 4 to 4.3 m
2000-10-25	18:11	4	20.8 min	Wires 3 and 4 to 16.4 m
2000-10-25	19:04	4	4.3 min	Wires 1 and 2 to 4.3 m
2000-10-25	19:27	4	19.7 min	Wires 1 and 2 to 16.4 m
2000-10-26	13:45	4	1.8 min	Spin-up to 22 rpm
2000-10-30	15:06	4	33.8 min	Wires 3 and 4 to 36.5 m
2000-10-30	16:08	4	8.1 min	Wires 1 and 2 to 21.4 m
2000-11-02	16:14	4	48 s	Spin-up to 17.5 rpm
2000-11-02	16:50	4	10.3 min	Wires 3 and 4 to 42.5 m
2000-11-16	14:50	4	44.3 min	Wires 1 and 2 to 42.5 m
2000-11-16	21:15	4	2 min	Spin-up to 15.0 rpm
2000-11-28	18:11	4	5.4 min	Slew to operational attitude

COMMISSIONING PHASE AND BOOM DEPLOYMENT

After completion of the transfer orbit phase, the four spacecraft were manoeuvred to achieve the operational configuration, that is the operational spin rate of 15 rpm and the operational attitude aligning the spin axis almost perpendicular to the ecliptic plane. This is shown in Fig. 9.

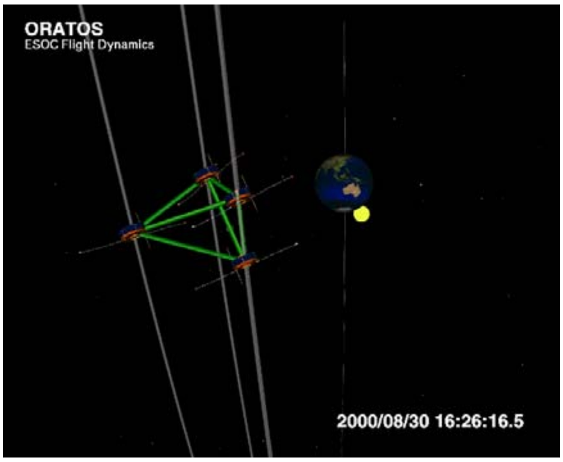

Fig. 9. Initial tetrahedron configuration

At the same time, accurate planning of the orbit trims necessary to equalise the periods of the four spacecraft within half a second, was prepared. Due to the sensitivity of the orbits to any attitude manoeuvre and the great number of attitude changes and spin rate adjustments required for the boom deployment, it was decided to perform the orbit trims during the period of the rigid and wire boom deployment. Therefore, the orbit perturbations from the boom deployment were always included in the manoeuvre optimisation process.

The deployment of the 5 m rigid booms and the four 43 m flexible cable booms on each satellite required a sequence of several attitude slews, and spin rate adjustments. To minimise the impact on the spacecraft constellation, careful monitoring of the orbit evolution and the spacecraft dynamics was necessary during this phase, which had to be spread over more than three months of the payload commissioning phase. A typical sequence of activities for the wire boom deployment is given in Table 5. From the processing of the telemetry, the nutation levels during rigid boom deployment for each s/c was estimated and the results are given in Table 6. The nutation observed were relatively small compared to data from the Cluster Users Manual which suggested that nutation could be as high as 6 degrees. However for Cluster II, was more fuel left onboard, compared with the original Cluster I scenario.

Table 6 – Nutation levels during rigid boom deployment

	-Y boom	+Y boom	-X boom
s/c 1	1.1 deg	1.7 deg	1.5 deg
s/c 2	1.1 deg	0.7 deg	0.2 deg
s/c 3	1.1 deg	0.5 deg	0.8 deg
s/c 4	1.2 deg	1.9 deg	1.3 deg

To achieve the desired constellation a sequence of orbit trims had to be performed, from the configuration achieved at the end of the transfer phase to a constellation drifting towards the target at the time of the central crossing of the scientific region. The standard sequence of manoeuvres for constellation change foresees the following: a drift start manoeuvre close to the perigee, two corrections close to the apogee and performed using the radial and the axial thrusters, and finally a drift stop manoeuvre. Due to the orbit impact from the attitude changes and spin rate adjustment, a small number of additional trims needed to be performed at the end of the wire boom deployment.

By the end of August 2000, all four spacecraft had completed the rigid boom deployment and the major constellation acquisition manoeuvres. Spacecraft 2 and 1 were the first pair to start the wire boom activities spread over one month from the beginning of September; this was followed by spacecraft 3 and then spacecraft 4. By mid-November, these activities were completed on the four spacecraft. Very small orbit trims, typically two for each spacecraft were required to eliminate the undesired effects on the orbit. At a time close to the cusp crossing time, the mean inter-spacecraft distance was 603.5 km and all inter-spacecraft distances were within 5 km of each other. After the complex period of spacecraft commissioning, during which 44 separate instruments were verified and tested, and 64 boom deployment sequences were performed, full scientific operations started on 1 February 2001.

ROUTINE PHASE

During the routine phase, telemetry, commanding and tracking is handled at ESOC using primarily the ESA ground station of Villafranca, Spain. The major activities are the control of spacecraft and their payloads, and carrying out all activities related to mission planning and scheduling.

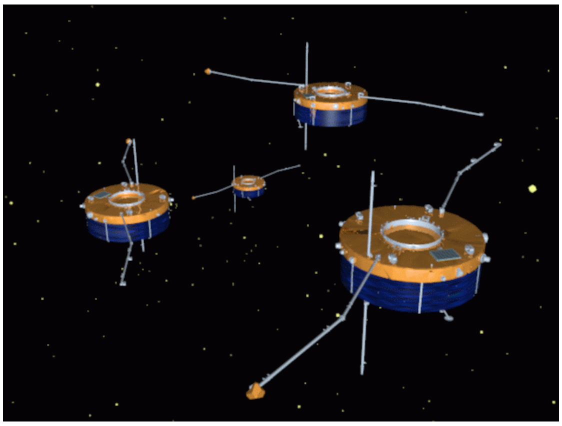

Figure 11 – Spacecraft in operational orbit

The operations are partially interrupted during the time in which orbit manoeuvres are performed to adjust the separation distances between the four spacecraft. The first constellation for the cusp crossing at the end of February 2001, was implemented with the spacecraft 600 km apart. The next block of orbit manoeuvres was performed in May 2001 to adjust the inter-spacecraft distance to the value of 2000 km required for the tail crossing, in September 2001. At a time close to the neutral sheet crossing time, the mean inter-spacecraft distance was 2003 km and all inter-spacecraft distances were within 10 km of each other. Thereafter, another cusp crossing is planned with spacecraft separation at 100 km in February 2002. Finally there will be a return to the magnetotail constellation with spacecraft separation of more than 5000 km.

Each change in separation distance requires about 20 manoeuvres in total (including the very small orbit trims), and it is performed by following the standard strategy. In addition, the spacecraft attitude has to be regularly corrected approximately once every three months, in order to maintain the solar aspect angle within the allowable range of 93.2 to 96.2 deg (avoiding shadowing of the payloads by the booms). This is done by executing a single attitude manoeuvre per each spacecraft. A very small change in the spin rate of the four spacecraft can be observed. This is mainly due to energy dissipation because of the oscillatory motion of the booms. The spin rate was corrected only once after the boom deployment activities, in May 2001, and brought very close to 15 rpm.

One of the main factors influencing the data acquisition and the spacecraft control is the limited time available for ground contact for each spacecraft. On average the spacecraft are visible for about 10 hours per day from Villafranca. However, the time available to acquire data from each spacecraft is around two and half hours per day. Accurate planning of all the foreseen activities, prepared long in advance, is one of the important tasks of the Flight Control team during the routine phase.

CONCLUSIONS

An overview of the major operations and Flight Dynamics activities performed during the Cluster II mission was presented in this paper. The challenging aspects of this mission were mainly the interfaces with the launch authority at the Lavochkin complex in Moscow and at Baikonour and the execution of parallel operations for two and then four spacecraft in a short time span. Accurate planning of all operations was mandatory in order to follow the nominal mission. This required the development of dedicated tools able to update in quasi-real-time the mission plan, each time the need arose. Mission plan and operational procedures were extensively checked for completeness and feasibility during many hours of simulations campaign and system tests. The complex manoeuvre optimisation software, operationally used to achieve and maintain the spacecraft constellation, computed very sophisticated manoeuvre strategies able to meet the constraints and the targets of the mission with the minimum fuel.

The experience gained in the field of multi-satellite operations planning and constellation acquisition and maintenance could provide important contributions to other future space programmes, for example Galileo, in which the operational planning of constellations will play a key role.

In addition, one has to mention the agreement of the international scientific collaboration between ESA and the Chinese National Space Administration for the Double Star programme. Double Star will follow the Cluster mission by studying the effects of the Sun on the Earth's environment. Conducting joint studies with Cluster and Double Star should increase the overall scientific return from both missions. Finally, more details on the overall mission, spacecraft and payload can be found by visiting the ESA web site at http://spdext.estec.esa.nl/.

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